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Technical pathways to deep decarbonization in cities: Eight best practice case studies of transformational climate mitigation

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A R T I C L E I N F O

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A B S T R A C T

As the urgency for climate action heightens, local governments and stakeholders are developing pathways towards deep decarbonization at the local level and committing to community-wide greenhouse gas reductions of 80–100% by 2050 or earlier. Urban areas are the largest place-based source of greenhouse gas emissions, accounting for 71%–76% of global emissions. Local governments have direct and indirect control of over a significant proportion of emissions that occur within their municipalities. However, there remains a gap in knowledge about the local technical and policy pathways that are being developed in order to achieve deep decarbonization and how these pathways vary for different size cities. This study qualitatively analyzes eight local government deep decarbonization plans of cities that range in size from eight thousand to nine million people. We analyze emerging patterns among the cities, while also considering the impacts of the population size and the national context. Each city has unique circumstances and priorities when it comes to decarbonization, and not all cities prioritize their highest emitting sectors for decarbonization. We find that emerging technical pathways to deep decarbonization focus on five priority sectors (electricity, buildings, transportation, waste, and carbon sinks and storage), but also that several local governments are developing innovative strategies beyond what is described in the literature for decarbonizing the priority sectors within their jurisdiction and are expanding the scope of their plans to include emerging areas in GHG mitigation such as scope 3 and embodied greenhouse gas emissions.

1. Introduction

In order to reach global reduction targets for greenhouse gas (GHG) emissions, cities and urban areas will be at the forefront of deep decarbonization practices [1]. Urbanization is occurring at accelerating rates all over the world. In 2018, roughly 55.3 percent of the global population lived in urban settlements and that number is projected to increase to 60 percent by the year 2030 [2]. Cities are the largest place-based source of GHG emissions, accounting for 71%-76% of global emissions [3]. Local governments have control directly and indirectly over 52% of emissions that occur within their cities and/or municipalities [4,5].

Overall, national commitments to climate action under the 2015 Paris Agreement will be insufficient to contain a temperature rise at 1.5 °C [6] and in 2018 the Intergovernmental Panel on Climate Change (IPCC) spelled out the necessity of significantly more ambitious global climate action to have a chance of limiting global warming to 1.5 °C [7]. Rapid and far-reaching transitions must occur with targets of at least 45% in global emissions reduction by 2030 and carbon neutrality by 2050 to have a chance of limiting global warming to 1.5 °C [7]. These deep decarbonization milestones are considerably more ambitious than climate action to date and require transformational change to be achieved [8]. Considering this reality, many local governments are starting to recognize the need to achieve net-zero GHG emissions and are pursuing deep decarbonization. Going beyond the previous scope of local climate action, these cities have pledged to the 80 by 50 target (at least 80% reduction of community-wide GHG emissions by the year 2050) and have created extensive plans in order to reach their goals [9,10]. As local governments around the world are increasingly committing to even more ambitious GHG reduction targets, there remains a gap in knowledge about the local pathways and actions that are being developed in order to reach the targets in diverse cities.

Decarbonization is defined as “the process toward fossil energy being a vanishingly small part of the energy mix” [11]. The core idea behind

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decarbonization is disrupting carbon lock-in, which can be described as path dependent processes where "the inertia of technologies, institutions and behaviors" limits systemic transformations [12] and "perpetuates fossil fuel-based infrastructures" despite known, costly damages and cost-effective alternatives [13]. Decarbonization can be accomplished while also considering broader sustainability goals such as climate adaptation, social equity and institutional transitions [14,15]. For the purposes of this article, we define local deep decarbonization as pursuing 80–100% net reduction in GHG emissions by the year 2050 or before. Currently, most deep decarbonization pathways produced by local governments focus on scope 1 (i.e. GHG emissions from sources located within the city boundary) and scope 2 (i.e. indirect GHG emissions associated with the purchase of electricity, steam, and heating/cooling that are generated outside the city boundary but are consumed inside), though as discussed later, leading cities are now also considering scope 3 emissions (i.e. all other GHG emissions that occur outside the city boundary as a result of activities taking places within the city boundary), embodied carbon, and carbon sinks.

This study examines eight case study cities of various sizes and nationalities in order to determine which technical and policy pathways to deep decarbonization are being developed by local governments of different size cities. Through examining these case studies, we aim to answer the following questions:

1. What are the technical and policy pathways to deep decarbonization being developed in the plans of local governments targeting 80–100% net reduction in GHG emissions by the year 2050 or before?
2. Are there systematic differences between the plans of cities with small and large populations?
3. In what ways are climate action plans well aligned with research-based recommendations on deep decarbonization strategies, and what gaps do they exhibit?

We synthesize academic and grey literature findings about what these pathways should look like and the pragmatic learnings from implementing local government decarbonization plans. This study offers a compilation of local deep decarbonization pathways from academic literature that has been empirically validated and expanded upon by eight case cities of varying sizes. Our work contributes to urban studies, climate mitigation and sustainability management literatures and to the implementation of the Sustainable Development Goals numbers 11 (sustainable cities and communities) and 13 (climate action).

This paper begins by summarizing the key knowledge in the local deep decarbonization literature, followed by the methodology for the data collection and analysis. The results and analysis of the data are presented next, followed by a discussion of the findings, and lastly, the conclusion and future research.

2. Technical and policy pathways for deep decarbonization in cities & communities

There are existing studies on the state of climate action planning and implementation at the local level, for example Deetjen et al. [16] did a review of 29 climate action plans in American cities and found that many of them lack cohesiveness within their plans and may be unsuccessful in reaching GHG mitigation targets without re-evaluating their plans. Local climate action plans have been studied in terms of their content, effectiveness and similarities and differences [17] and researchers have developed frameworks for the improvement and adoption of community-wide climate action [18]. However, few papers have specifically focused on significant GHG emissions reductions, or analyzed how a diversity of local governments are approaching deep decarbonization pathways in terms of the technical and policy tool components. This study examines cities in different countries and of different sizes where the local government is specifically targeting local deep decarbonization in order to advance our understanding of the technical and policy components of local government plans aiming for deep GHG emissions reductions.

Technical and policy pathways for deep decarbonization are important for planning and tracking the changes consistent with the targets and goals that have been set out, as they provide a common method by which governments, business, civil society and researchers can communicate and compare differing visions and progress [9,19,20]. Technical and policy pathways for GHG mitigation and deep decarbonization consist of the goal or target itself and the pathways to that goal. For the purposes of this paper, the pathways include the technologies used, the nature of coordination and collaboration of actors, and the policies implemented for the most relevant sectors; in essence they consist of the near term and future choices that must be made to reach decarbonization targets [21]. The pathways are organized by sector, and can aid in the design and implementation of short-term policy packages that are consistent with long-term global GHG reductions [20]. We focus on unpacking technical and policy pathways for deep decarbonization to shed light on technologies, targets and policies, but recognize that this is just one aspect of deep decarbonization. It is crucial to also recognize that transformative action to address climate change depends on a broader consideration of economic, cultural and political components of power dynamics [1].

At the local level, there are two types of climate action plans: corporate and community. Corporate plans reflect the direct control that local governments have over their own operations (e.g. local government buildings, vehicle fleets, etc.) [5,10,22]. Community climate action plans consider all GHGs emitted within the local geographic boundaries of the community, including emissions from industry, home heating, burning fuel in private vehicles, etc. [23–25]. This study focuses on community-wide plans but also takes into account corporate targets and actions.

Brozynski and Leibowicz [26] propose that technical pathways for decarbonization consist of two sequential stages. The first is to decarbonize the electricity sector and then shift focus to the transportation sector [26]. This has been extended to outline five elements of achieving deep decarbonization: 1) maximize energy efficiency in order to reduce the energy needs that must be met, 2) decarbonize the electricity supply by switching to renewable and zero emission sources of energy, 3) transfer clean electricity into other sectors such as transportation and buildings, 4) use zero-carbon fuels for the remaining areas that cannot be effectively electrified, and 5) use carbon capture and carbon dioxide removal for areas where fossil fuels are still needed as well as for achieving negative emissions [7,9,20,27,28].

In cities, the four priority sectors for decarbonization can be identified as: energy, buildings, transportation and waste. These sectors represent the vast majority of city-wide emissions and local governments have a degree of control and/or jurisdiction over them [5,9,20]. For the purposes of this paper, we clarify that the energy sector is the electricity sector. The term energy implies an overlap between sectors, for example it can include emissions from transportation fuels and from heating and cooling systems in buildings. We make a distinction between the sources of emissions from all of these sectors, and so transportation fuels fall under transportation, and heating and cooling buildings fall under buildings.

By tackling these main sources of emissions (among other actions such as increasing carbon sink capacity), deep decarbonization is technically feasible [20]. Along with the technical pathways that address GHG emissions by sector, cities institutionalize deep decarbonization by taking actions that ensure the commitment and involvement of stakeholders [9]. Table 1 summarizes the priority sectors for deep decarbonization in cities according to the current academic and grey literature.

Table 1
Priority Sectors for Deep Decarbonization in Cities.

Sector	Finding/ Contribution	Source
Electricity	Electricity is a priority sector, and decarbonization can be done by removing unabated fossil fuels entirely from the electricity grid. Local governments have limited control over this sector, but they can utilize building scale and district energy solutions. Also, sometimes they own local utilities.	[26,27,29]
Buildings	New and existing buildings need different approaches. Existing buildings can be decarbonized through retrofits and new buildings can be constructed to be net-zero. Zero emissions heating/cooling systems and improving energy efficiency are the top priorities for decarbonizing buildings. Local governments can implement low carbon or zero carbon building performance/energy standards and regulations if they have the jurisdiction, or they can offer incentives and education.	[9,30,31]
Transportation	Transportation decarbonization includes mode shift and fuel shift. Local governments have limited direct control over this sector other than local government owned fleets, electric vehicle (EV) infrastructure and public transit. Local governments can have significant influence over transportation by offering incentives, using market based instruments (MBIs), developing active transport infrastructure, and planning for urban design to reduce emissions associated with transportation.	[9,32,33]
Waste	Emissions from the waste sector can be mitigated through decreasing the amount of waste sent to landfills. This can be done through increased recycling and diversion measures. Non-recyclable waste can be converted to energy by incineration or biogas production. Gas capture systems can be installed to capture emissions as landfill waste breaks down.	[9,34–36]
Carbon Sinks and Offsets	Local governments can preserve and increase natural carbon sinks, such as forests, vegetation, wetlands, and soils. Local governments can also purchase carbon offsets to balance their emissions.	[37,38]

3. Methods

3.1. Research design

This study uses qualitative case study methods and takes a descriptive role rather than a critical one by outlining the current status of climate action planning in the selected case studies [39]. This type of descriptive research allows for the exploration and discovery of what is occurring in the case studies [40,41]. Through this approach, this study aims to explore which technical and policy pathways to deep decarbonization are being developed by local governments of diverse cities. The purpose of this study is to be socially relevant and aims to generate insight for researchers, policy makers, practitioners and stakeholders [42]. While this exploratory study makes no predictions or judgements, it opens the door for further research using mixed or quantitative methods [43].

To ensure internal validity, data from multiple sources were collected for each case study, including the climate action plans, the Carbon Disclosure Protocol (CDP) Cities database and interviews with municipal representatives, and triangulation of sources was used to establish the validity of the data and to protect against researcher bias [44]. The coherence of findings in the data analysis phase was assured by cross-checking the results [45] and cross-case pattern matching was also used in the data analysis phase [46]. To ensure external validity, replication of the research design was used for all eight of the case studies [47] and the scope and boundaries were also defined in the research design phase in order to achieve reasonable generalizations for the research [46]. To ensure construct validity regarding the design of the study, a detailed literature review on deep decarbonization at the local level was conducted [45].

3.2. Case selection & data collection

The Carbon Disclosure Protocol (CDP) Cities 2019 database was used to identify cases with GHG reduction targets that met the definition of this study (80–100% reduction by 2050 or sooner). The CDP provides a global platform for cities to annually report and disclose environmental information and provides public, open-access data on all the voluntary reporting of the cities [48]. In 2019 the CDP partnered with ICLEI Local Governments for Sustainability, C40 and Global Covenant of Mayors in order to streamline the city climate reporting process and to present a unified platform of reporting [48]. Over 625 cities from around the globe voluntarily reported to the CDP in 2019.

This study was co-designed with ICLEI Canada – Local Governments for Sustainability and, as a result of this partnership, a focus was placed on Canadian cities. Of the 625 cities that had reported in 2019, 17 of them were Canadian. The 17 cities were categorized by population size; very large (1 million and more), large (500,000–1 million), medium (50,000–500,000) and small (50,000 or smaller). The following criteria were used to select case study cities: ambitiousness of GHG mitigation targets (80% or more by 2050), a publicly accessible written climate action plan document, implementation of the plan underway, and reported decrease in overall GHG emissions since the implementation of the climate action plan. Four Canadian cities were selected (one in each of the population size categories based off of the above criteria).

Following the same process that was taken to select the Canadian case studies, four cities from other countries were then selected as case comparisons for the Canadian ones. The non-Canadian cases that were selected met all of the criteria above and were the closest in population to the Canadian cases. Table 2 summarizes the eight cases that were chosen, along with their population sizes, their overall GHG reduction targets as well as the pairings of Canadian and non-Canadian cities by population size. The climate action plans used for data collection are also referenced for each case study. A research design comparing eight cases has limited space to include background context descriptions for the cases but provides opportunities to compare a wider range of decarbonization technical pathways due to the inclusion of a range of city sizes in multiple international contexts.

Table 3 demonstrates the breakdown of community-wide emissions per sector for each of the case studies. Detailed data for Bridgewater and Lahti is currently not available. Some of the cases (Guelph, Toronto and New York) have combined the emissions from the electricity and buildings sectors.

Data were collected from publicly available documents (e.g., local government climate action plans, annual reports, and other publications) and then through semi-structured interviews with representatives from the local governments. Background data, both from publicly available sources and internal archival sources, were used to develop the background for each case study. Online documents, reports and articles were collected and analyzed for information pertaining to the research questions. Other documents such as academic and newspaper articles, and third party reports and studies were also collected as they are also valid sources of data for document analysis [62]. The CDP 2019 Cities database was also analyzed as a key source of information for the data collection.

Semi-structured interviews were conducted with key actors from five of the case cities. The objective of the interviews was to gather information pertaining to the research questions that was not available or clearly specified in public documents. Project managers from all of the

Table 2
Case selections.

City	Size	Population	Reduction Target %	Target Year	Baseline year	Climate Action Plan Document (s)
Bridgewater, Canada	Small	8,532	80	2050	2011	Energy Poverty Reduction Program [49], Community Energy Investment Plan [50]
Park City, USA	Small	8,376	100	2030	2007	Community & Municipal Carbon Footprint [51]
Guelph, Canada	Medium	131,794	100	2050	2016	Community Energy Initiative Update [52], Pathways to Zero Carbon [53]
Lahti, Finland	Medium	120,028	80	2025	1990	Sustainable Energy and Climate Action Plan [54]
Vancouver, Canada	Large	642,686	100	2050	2007	Greenest City Action Plan [55], Climate Emergency Action Plan [56]
Oslo, Norway	Large	673,469	95	2030	1990	Oslo's Climate Budget [57], Oslo's Climate and Energy Strategy [58]
Toronto, Canada	Very Large	2,929,886	80	2050	1990	TransformTO plan and implementation update [59]
New York, USA	Very Large	8,622,700	80	2050	2005	Roadmap to 80x50 [60], OneNYC – A Livable Climate [61]

Table 3
Emissions by sector.

City	Electricity	Buildings	Transportation	Waste	Year
Bridgewater, Canada	–	–	–	–	–
Park City, USA	36.3%	23.4%	37.1%	3%	2016
Guelph, Canada	60.7%		32.4%	7%	2016
Lahti, Finland	–	–	–	–	–
Vancouver, Canada	~0%	55%	41%	4%	2016
Oslo, Norway	3%	17%	61%	19%	2017
Toronto, Canada	55%		36%	9%	2018
New York, USA	66%		30%	4%	2016

cities were contacted via email, five of which responded and consented to be interviewed. For the remaining three cities, it was determined that there was sufficient information in publicly available documents and databases to conduct the study without an interview.

Interview guides were developed specifically for each case study based on information that was unavailable in public documents (see Appendix 1 for interview guide of potential questions). The interview questions related to the GHG emissions reduction targets of the local government for each priority sector and the types of actions that were being implemented to reach their deep decarbonization goals. Data were analyzed by deductively coding the content of the documents and interview transcripts according to the five priority sectors for local deep decarbonization identified in the literature review (electricity, buildings, transportation, waste, carbon sinks and offsets). This information was reduced into summaries by sector for each case (Appendix 2) and then further synthesized for cross-case comparison in the results and analysis section.

4. Results and analysis

The results analyzing the technical and policy pathways to deep decarbonization in the plans of the local government case studies are presented for each of the case studies, organized by the five priority sectors for deep decarbonization that were outlined in the literature review. For each case, the targets and the actions are outlined in each of the priority sectors for deep decarbonization at the local level. Table 4 shows a synthesis of the results and a cross-case comparison of the targets for each of the cases to highlight emerging patterns across the case

Table 4
Cross-case comparison: targets.

	Electricity	Existing Buildings	New Buildings	Mode Shift	Fuel Shift	Waste	Carbon Sinks & Offsets
Bridgewater	44 MW of renewables installed by 2050	Improve efficiency by 50%	Net-zero buildings by 2030	50% short trips walking or biking	100% EV by 2050	No target	No target
Park City	100% renewable by 2030	No target	Net-zero municipal buildings	No target	100% electric transit by 2026	No target	Capture remaining emissions
Guelph	100% renewable by 2050	Retrofit 98% of buildings by 2050	Net-zero buildings by 2030	Increase cycling & walking trips, double rideshare trips	Electric transit and fleet by 2050, 100% EV passenger vehicles	70% diversion by 2021	Offset 8% of emissions by 2050
Lahti	~100% renewable by 2020	7% efficiency increase by 2025	Low energy municipal buildings	50% short trips walking or biking by 2030	100% electric/bio gas transit by 2030	100% diversion by 2050 (currently 96%)	Capture ~ 20% emissions by 2025
Vancouver	Currently ~ 97% renewable	Reduce GHG emissions in buildings by 20% by 2020	Net-zero buildings by 2030, reduce embedded emissions by 40%	66% short trips walk/bike/transit by 2030	50% EVs by 2030, electric fleet and transit by 2050	100% diversion by 2040	Capture 1,000,000 tonnes CO2/year by 2060
Oslo	Currently 100% renewable	Zero/low emissions heating in all buildings by 2020	Net-zero municipal buildings by 2020, reduce embedded emissions	Reduce traffic 33% by 2030, 25% trips by bike by 2025	EV transit by 2020, 100% EV by 2030	100% diversion	No target
Toronto	75% renewable by 2050	Retrofit 100% buildings for 40% efficiency increase by 2050	Near zero buildings by 2030	75% short trips walk/bike	100% low/zero carbon vehicles by 2050, EV transit by 2040	95% diversion by 2050	No target
New York	100% renewable by 2040	Retrofit all government buildings, increase efficiency in large buildings 80% by 2050	Net-zero buildings by 2030	80% short trips walk/ bike/ transit	Carbon neutral fleet by 2040, 20% of vehicles for sale are electric by 2025	100% diversion by 2030	Offset remaining emissions

studies. Additional details, including specific technologies, policies, and anticipated costs outlined in each climate action plan are available in Appendix 2.

Table 5 shows a cross-case comparison of the types of policies and actions that each of the cases are developing and implementing in order to reach their targets in each of the sectors (see Appendix 2 for additional details).

4.1. Electricity

Many argue that the technical pathway to decarbonization should begin with the electricity sector, followed by efficiency gains and electrification in other sectors [27]. The elimination of unabated fossil fuels from the electricity sector is needed to address ambitious climate goals in cities [26,27,65–67]. The empirical results validate the literature; all of the case cities have targets to significantly increase the capacity of renewable electricity. Park City, Lahti, Guelph, Vancouver, Oslo and New York have targets to derive 100% of their electricity from renewable sources by or before 2050.

Table 5
Cross-case comparison: policies and actions

Sector	Actions		City
Electricity	Build Renewable Energy Systems		Bridgewater, Park City, Guelph, Lahti, Toronto, New York
	District Heating		Bridgewater, Guelph, Lahti, Vancouver, Toronto, New York
	Building Scale Electricity Generation		Guelph, Toronto, New York
Buildings	Existing Buildings	PACE Program	Bridgewater, Park City, Guelph, New York
		Financial Incentives	Park City, Vancouver, Oslo
		City-Owned Building Retrofits	Guelph, Vancouver, Oslo, Toronto, New York
		Building Regulations/ Mandates	Vancouver, Oslo, New York
		Low Interest Loan	Toronto
	New Buildings	Building Codes/ Mandates	Vancouver, New York
		Voluntary Building Code/Performance Standard	Bridgewater, Park City, Guelph, Toronto
		Regulation for Heating Systems	Oslo
		City Owned Building Code	Park City, Lahti
Transportation	Mode Shift	Infrastructure Investments	All
		Financial Tools Market Based Instruments	Park City, Lahti, Oslo, New York
		Regulations (Restricted Vehicle Zones)	Guelph, Oslo Toronto, New York
	Fuel Shift	Electric Fleet & Transit Investment	All
		EV Charging Infrastructure	Park City, Guelph, Lahti, Vancouver, Oslo, Toronto, New York
		Financial Incentives	Park City, Oslo
		Regulations	Oslo
Waste	Capture Landfill Gas		Guelph, Lahti, Vancouver, Oslo, Toronto, New York
	Supporting/Enabling Actions		All
	Waste-to-Energy Systems		Lahti, Vancouver, Oslo, Toronto, New York
Carbon Sinks & Storage	Restore Local Carbon Sinks		Park City, Lahti, Vancouver
	Purchase Carbon Offsets		Guelph, New York

The literature notes that in many cases, local governments do not have direct control over their sources of electricity [66,68]. Due to this, some cities are using a variety of other strategies recommended in the literature, including developing partnerships with utilities and advocacy actions. Park City and Lahti (the cities with the most ambitious renewable energy targets) have both leveraged public/private partnerships in order to build large-scale renewable energy generation facilities. By partnering with their local utility companies, they have managed to rapidly decarbonize their electricity grids as well as heating systems. Other cities have used a different approach to decarbonize the electricity grid. Park City has been a leader in advocating to the Utah State Government through its role in the creation of The Community Renewable Energy Act, which sets a framework to regulate procurement and pricing of large-scale renewables for communities in Utah that aim to have 100% renewable energy. Guelph, Toronto, and New York also use advocacy as a tool to express their demands to higher levels of governments for more renewable energy.

4.2. Existing buildings

Retrofits of existing buildings are critical in the decarbonization of cities. Existing buildings must be energy efficient and have heating and cooling systems that do not rely on fossil fuels [31,69]. Retrofits can result in lower energy costs [70,71], though the results show that this is dependent on location and energy prices [9]. Municipal governments can prioritize GHG reductions in existing buildings through updates to efficiency standards and providing incentives for retrofits; they can also lead by example as an owner/investor of a substantial portfolio of buildings [30,72]. Urban energy retrofitting is a challenging area of decarbonization, but some previous attempts have highlighted the importance of targeting owners of multiple buildings, expanding the suite of supporting resources, experimenting and teaching using public investment, and institutionalizing energy and carbon reporting [72].

The empirical results show that cities acknowledge that retrofits are a key aspect of decarbonization. Many of them have set retrofit targets and efficiency improvement targets. Cities such as Toronto, Vancouver, New York, Guelph, and Oslo are leading by example with retrofits to their own building stock. Furthermore, providing tools and incentives for residents and businesses/organizations to take action is a common strategy. Financial tools and incentives such as the Property Assessed Clean Energy (PACE) program, help residential and commercial building owners finance energy efficiency and renewable energy improvements on their properties. Bridgewater, Park City, Guelph, and New York have all implemented PACE programs that are available to private building owners. Other financial tools being used include low interest loans (Toronto), discounts and rebates (Lahti, Vancouver), and efficiency tool kits (Park City), all are being used in order to influence building owners to retrofit.

Vancouver and New York City have taken on a much more ambitious strategy through the development of their own building regulations. These two cities have the legal authority under their city charters to develop their own building codes, which have been extended to apply to existing buildings. They have also created networks to help to connect building owners with technical experts and to help educate and engage them.

Cities can also deploy building-scale and district clean energy solutions to decarbonize heating and cooling systems for buildings [66]. All cases except Park City are looking into this or are continuing to expand their current networks.

4.3. New buildings

To limit emissions from new buildings, cities that have the legal jurisdiction to do so, can implement building codes and standards for new developments [31]. Cities can also lead by example by building their own developments to produce zero emissions [30]. The empirical results validate the literature. All of the case cities have opted to lead by example and set strict regulations for efficient or net-zero buildings if they are city-owned. All of the cities have also developed building standards or codes (voluntary or mandatory) for new developments.

There are few examples of cities implementing their own mandatory building codes because of the limited legal jurisdiction of cities. Vancouver is the only city in Canada that has enacted its own building code because it is one of the only charter cities in the country that has the power to do so. The Vancouver Building Code will ensure that by 2030, all new buildings will be net-zero emissions. Toronto has developed the Toronto Green Standard (under the City of Toronto Act 2006), which is a tiered system; tier one being mandatory and tiers two to four being voluntary. The City of Toronto offers financial incentives for builders to adhere to the voluntary tiers.

Bridgewater, Guelph and Park City must follow provincial/state building codes. Both Lahti and Oslo are following their national building requirements, including the national ban on fossil fuel heating in Norway (for Oslo). New York City is the only city in the State of New York that is permitted to retain its own building code. The City has taken advantage of this and has implemented efficiency regulations for various building types.

Cities can influence efficiency and energy behaviour for buildings, they can also act as a regulator, convener, facilitator, as well as a strategic partner [30,69]. The empirical evidence shows that cities are developing and managing networks to influence building performance including the Building Energy Exchange (BEex) program (New York), Better Building Partnership (BBP) (Toronto), and the Zero Emissions Buildings Center of Excellence (Vancouver). The purpose of these programs is to educate and build capacity for building owners and developers. Vancouver and New York have been developing and supporting programs to help increase the capacity for green construction and Zero Emissions Buildings construction.

Embodied emissions account for a large percentage of emissions within a building's lifecycle [73]. Vancouver is aiming to reduce embodied emissions in new buildings and the City has developed an embodied carbon strategy. This strategy will set embodied carbon limits for new construction. Oslo has also been piloting fossil-free construction sites, which are now a requirement for City-owned buildings and developments. The City is looking into implementing regulations for eliminating emissions from construction by 2030. These are two examples of forward thinking strategies that will enable embodied carbon to be considered.

4.4. Mode Shift

Transportation mode shift can be influenced though the promotion and increase in the use of zero emissions modes of transportation (e.g. walking, biking) [9,66,74]. Local governments can invest in infrastructure that supports their climate action targets, such as pedestrian walkways, bike lanes, and electrified public transit [9,66,75,76]. Cities can also manage how streets are used through rules, regulations and pricing [9].

All of the cases are targeting increases in walking, biking and public transit trips and are investing in pedestrian, bike and public transit infrastructure to reach their targets. By improving accessibility and safety of active and public transit, the case cities are anticipating that their citizens will opt to walk, bike or take public transit. Oslo, Toronto, New York and Guelph are considering or have gone ahead with car free or restricted vehicle access zones as well as removing or limiting parking spaces in key areas as a way to remove perverse incentives that may influence residents to use personal vehicles. Some cities are going further, providing incentives to choose active or low carbon forms of transport and dis-incentivising single passenger vehicles by using market based instruments (MBIs). These incentives or MBIs include: paid parking (Park City), toll rings (Oslo), congestion pricing (NYC), free public transit (Park City), active transportation rewards (Lahti and Guelph). The City of Lahti has partnered with local universities and local businesses to develop the CitiCAP program. This program is a personal cap and trade system where users record their transportation habits, their carbon footprint will be calculated, and users with low footprints are rewarded with various discounts and incentives.

4.5. Fuel shifting

The literature indicates that the scope for local policies that affect vehicle emissions is limited outside of fleet-based operations [69]. However, cities can develop creative ways to impact the vehicle choices of their residents by providing prime parking spots for zero-emission vehicles and raising road prices for larger vehicles. Local governments could also mount social marketing campaigns in support of climate-friendly vehicles [69].

All of the cities have a target in place for the decarbonization/fuel shift in their own fleet and/or transit operations. Cities are also building EV infrastructure to incentivise residents to purchase and drive more electric vehicles. Vancouver has included in its building code that for multi-family and commercial buildings, wiring for EV charging stations must be built into parking stalls. Oslo and Park City have implemented financial incentives for electric vehicles. Oslo's toll ring system charges lower prices for zero emissions vehicles and Park City provides free charging for EVs in the city.

Though cities are helping to enable transitions towards zero emissions vehicles, they are mostly relying on higher levels of government and the automotive industry to push a shift. Due to the lack of regulatory control in this sector, local governments make use of enabling and provisioning governance tools.

4.6. Waste

The literature concludes that the main emissions reductions in the waste sector are associated with reducing the amount solid waste going to landfills [35,36,77]. Cities can divert waste that would previously go to landfills through several processes, including public education initiatives on waste reduction, changing procurement to support circular economies and zero waste, and increasing recycling and composting services. Non-recyclable materials can also be converted into usable energy (heat, electricity or fuel) through a variety of waste-to-energy processes [34]. Emissions from existing landfills can also be minimized through the installation of landfill gas capture systems [34].

The results show that six of the eight cities have their own solid waste plan with targets to reduce waste sent to landfills and an outline of activities that the cities are co-ordinating for community-wide waste reduction. Park City and New York have banned plastic bags in order to influence upstream purchasing that results in less waste creation. Park City is investigating composting systems for the city and New York expanded its composting pick-up services, but then largely scrapped the program. Because Bridgewater and Park City share waste management systems with other municipalities in surrounding regions, they focus on education or enabling actions to encourage their citizens to reduce their solid waste output.

Research has shown that successful waste management strategies for climate action should emphasize diverting waste from landfills as well as incinerators [9,77]. In that context, local governments are also making use of waste streams and capturing GHG emissions. To decrease methane emissions associated with the waste already in landfills, Lahti, Vancouver, Oslo, Toronto and New York have built gas capture systems for existing landfills. The cases are also using waste as a form of energy through different waste-to-energy processes for heating and through biofuel for transportation. Lahti built a biofuel plant that uses agricultural waste and sewage to power the city. Toronto, Oslo, and Lahti make biofuel from their organic waste so that the trucks that pick up waste can run on it, creating a closed loop system. The Klemstrudd waste incineration to district heating plant in Oslo is an example of innovation in the waste sector. A project was initiated to develop a full-scale carbon capture and storage system (CCS) for the incinerator. The Klemstrudd plant provides district heating to the city, and, with the CCS system in place, Oslo's community wide emissions will decrease by 12–15% alone [9,68].

4.7. Carbon sinks and offsets

Carbon offsets and sinks can be used to further GHG mitigation strategies after they have reached a threshold where all other means of mitigation have been exhausted [37]. Not all of the cases consider carbon sinks or offsets as a part of their emissions reduction plans, though Park City, Guelph, Lahti, Vancouver and New York all do.

Vancouver is investing in forest restoration, though the City will not count the GHG reductions as offsets. If offsets are going to be used, New York and Guelph are taking the approach that the literature recommends [37], by focusing first on eliminating sources of emissions and then making up the remaining difference with purchasing carbon offsets. Park City and Lahti will rely heavily on increasing capacity of local carbon sinks, both cities plan to capture and store enough emissions in local sinks in order to reach net-zero emissions. Park City focuses on protecting local land and increasing restorative agriculture to increase the capacity of local carbon sinks. Lahti is also taking these measures in addition to the City's consideration of using more wood in construction to act as a carbon sink. The discussion around the carbon storage potential of wooden buildings has recently been more prominent [78] and Lahti is the only case that is considering that strategy.

5. Discussion

In relation to the first research question, this study examined the technical and policy pathways to deep decarbonization being developed in the plans of local governments targeting 80–100% net reduction in GHG emissions by the year 2050 or before. The policy pathways developed by the case cities generally resemble each other with targets/goals, actions and indicators to measure progress. The technical pathways include but are not limited to the five priority sectors (electricity, buildings, transportation, waste and carbon sinks and offsetting) [7,9,20,28]. The results demonstrate that some cases are developing innovative strategies to decarbonize the priority sectors and several cases have added additional actions to include scope three and embodied emissions. These sources of emissions are not widely calculated and even less often targeted for mitigation action, therefore our findings show that some cities are beginning to include emerging areas for decarbonization action in decision making.

This study highlights that each city has a unique circumstance and priorities when it comes to decarbonization, though not all cities prioritize their highest emitting sectors for decarbonization. In some cases, the most accessible GHG reductions are in the "low hanging fruit" [7] rather than the sectors that emit the most. This demonstrates that while these are examples of cities ahead of the curve, there are still opportunities to further advance GHG reduction efforts in these places. Furthermore, some scope three and embodied emissions could be included in GHG inventories and cities could be developing consumption strategies to account for these emissions [64].

For the second research question, we examined systematic differences between the plans and actions of cities with small and large populations. The findings presented in this paper show that smaller cities have equally ambitious targets as larger ones and the actions outlined in their climate action plans are like those of larger cities. The main difference between cities with different population sizes is in the legal jurisdiction that the local government has over the main emitting sectors. Bigger cities tend to have more power over some of the priority sectors, for example, the cities of New York, Toronto and Vancouver all have the power to make and enforce their own laws and/or mandates in the building sector, while the other (smaller) cases were less likely to have any direct power over any of the sectors. We found that the smaller cities are working to leverage partnerships with the private sector or other entities to overcome jurisdictional challenges, which may result in more flexibility than larger cities. This study also highlights that local governments use enabling and engagement strategies when they do not have the power to enact policy for GHG mitigation.

Finally, for the third research question, we analyzed whether and how the case study climate action plans aligned with deep decarbonization strategies highlighted in the literature, which we consolidated into five priority areas: electricity, buildings, transportation, waste, and carbon sinks and offsets. Table 6 compares the literature review findings with the empirical evidence shown in the results. The comparison shows that deep decarbonization strategies described in climate action plans largely aligned with strategies highlighted in the literature. However, the table also highlights two areas where we found gaps in the grey and academic literature. In both the electricity and carbon offsets and sinks sectors, the case study climate action plans extended beyond the actions and targets identified in the literature. Additional research can further examine local climate action in this area to further extend the literature.

6. Conclusions and future research

We examined best practice examples of cities pursuing 80–100% net reduction in GHGs by the year 2050 or before to provide insights on the technical and policy deep decarbonization pathways that leading local governments are developing. Building on content that was mainly found in grey literature on local climate mitigation, we found that emerging technical and policy pathways to deep decarbonization in local government plans focus on five priority sectors (electricity, buildings, transportation, waste, and carbon sinks and storage). We can see that some of the cases have ambitious timelines for their deep decarbonization goals and are on their way to reaching them. In other cases, there are fewer short-term targets or it is not clear how much progress they are making towards long term goals. While it is still too soon to see if these cities will meet their long-term targets, this is a swiftly evolving field of governance with new targets and measures continually being adopted by local governments. This study also concludes that leading local governments are developing innovative strategies for decarbonizing the priority sectors within their jurisdiction. Our study compliments existing literature on local deep decarbonization plans and expands on previous studies that study climate action content, evaluate and critique local climate action plans and provide frameworks [8,16–18] by demonstrating the pathways that a diverse array of local governments are developing to combat climate change.

As much of the current information on technical and policy local decarbonization pathways was found in grey literature, or is specific to one sector, this study offers a compilation of local deep decarbonization pathways for the academic literature that has been empirically validated by eight case cities of varying sizes. In addition to showing which areas of policy and technology local governments focus on for their decarbonization plans, this study contributes to practical knowledge for developing and implementing deep decarbonization plans at the local level. By studying the plans and processes of two small towns, this study was also able to contribute findings on the pathways and the strategies that small towns use in order to reach their GHG mitigation targets. Smaller cities use enabling and engagement strategies, particularly leveraging partnerships, to overcome limited jurisdiction in some areas, which may result in more flexibility than larger cities.

Further research is needed for pathways to decarbonization at the local level. Cities are increasingly committing to carbon neutrality or to 100% renewable energy [79]. Research is needed on broadening decarbonization targets to incorporate embodied and scope three emissions, and on more rural or urban–rural cities to determine how agricultural emissions should be included. Furthermore, deep decarbonization requires urban transformation to address root causes among

Table 6
Empirical evidence and literature comparison.

Sector	Literature	Empirical	Contribution
Electricity	Cities can utilize building scale and district energy solutions if they do not have full control over energy	All of the cases have made ambitious targets to decarbonize the electricity sector. Smaller cities tend to prioritize renewable energy generation	Align/ extend
Existing Buildings	Retrofits are necessary to improve energy efficiency and heating/ cooling systems must be converted to zero emissions systems	Local government are leading by example and retrofitting corporate owned buildings. They are also developing programs to educate and incentivise privately building owners to retrofit.	Align
New Buildings	Low or zero carbon emissions standards for new buildings	Local governments are implementing voluntary building codes, and in some cases mandatory ones.	Align
Fuel Shift	Local governments have little control other than the vehicles directly owned by the City. They can create incentives and use MBIs to influence residents to use zero emissions vehicles	All the cases are investing in electric public transit and EV charging stations throughout the cities.	Align
Mode Shift	Mode shift can be influenced through active transportation and public transit infrastructure investments and MBIs	All of the cases are investing in better pedestrian and bike infrastructure. Some cases are developing incentives to use walk, bike or use public transit, some cases are implementing regulations to reduce traffic in certain areas.	Align
Waste	Cities can reduce emissions in this sector by diverting waste from landfills or incineration by providing better services and/or enabling activities. Waste-to-energy infrastructure and landfill gas capture systems can also be built to limit emissions from this sector	Not all cities have direct control over waste management. Those that do are increasing diversion rates and installing gas capture and waste-to-energy systems.	Align
Carbon Sinks and Offsets	Local governments can purchase carbon offsets and/or increase the capacity of local carbon sinks	Most of the cases are including carbon-offsetting strategies to meet their GHG reduction targets. Some of the cases (Park City and Lahti) are developing strategies to increase local carbon sink capacity that are not yet discusses in academic and grey literature	Align/ extend

the connected issues of inequality, uneven development, and climate change [1]. Building on our findings on local deep decarbonization technologies, policies and targets, research can deepen our understanding of the cultural, economic and political dynamics that can drive urban transformation.

Additional research could evaluate the actions being taken to see if they are sufficient to achieve deep decarbonization goals within the timelines set out by local governments. For example, research could build on this study by estimating the impacts that proposed policy and targets will have on progress towards decarbonization, by comparing differential impacts expected from deep decarbonization actions, or by analyzing over time whether cities are reaching planned targets. Lastly, further study on small and mid-sized cities, and their capacity and jurisdictional challenges, would also enhance understanding about the potential for these cities to deeply decarbonize.

In conclusion, significant climate action is needed to limit the global warming to under 2 °C [7]. Cities have an important role to play in helping address the 71–76% of global emissions [3] that are generated from urban areas. By synthesizing existing grey and academic literature on potential technical and policy pathways, and validating it in eight ambitious cities of varying sizes, we show the current state of the leading edge of deep decarbonization planning, enabling others to build on this work.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices. Supplementary data

Appendix 1 and Appendix 2 are found in the supplementary data to this article, which can be found online at https://doi.org/10.1016/j.erss.2021.102422.

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